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(54) ALTERNATING CURRENT DYNAMO-ELECTRIC MACHINE WINDINGS

(71) We, INTERNATIONAL RESEARCH & DEVELOPMENT COMPANY LIMITED, a British Company, of Fossway, Newcastle-upon-Tyne 6, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to stationary windings in alternating-current dynamo-electric machines, especially air-cored windings such as those employed in the stators of machines having a superconducting winding on the rotor (see for example British Patent Specification No. 1,315,302), and as air-gap windings in iron-cored machines.

In a conventional machine such as an A.C. generator the stator winding is composed of conductor bars disposed in slots in an iron core and extending parallel to the axis of the machine. The ends of the conductors are connected by end windings which link together conductors spaced around the rotor in order to form the turns of the winding. The end windings are usually of involute form and lie on a frusto-conical surface. In such a machine the field is concentrated around the conductor bars by the iron core an the influence of the field on the end windings, which project beyond the core, is further reduced by the frusto-conical formation which takes the end windings away from the region of high field strength generated by the rotor winding.

In a superconducting machine the field ampere turns obtainable are so great that it becomes possible to dispense with the expensive and cumbersome iron core of the stator winding whilst maintaining an effective flux density equal to or greater than that of a conventional machine. Whereas the magnetic forces in an a.c. generator having armature conductors retained in slots in an iron core largely appear on the iron, however, in an air-gap winding or in the stator winding of a superconducting machine the forces appear on the conductors themselves.

In accordance with the present invention there is provided an alternating-current dynamo-electric machine having a rotor, and a stationary alternating-current winding carried by a non-magnetic hollow cylindrical support structure coaxial with the rotor, the winding including a pair of coaxial cylindrical layers of conductors of which each conductor is composed of one or more sections of helical formation, each conductor of a layer having the same spatial relationship to the other conductors of the winding as every other conductor of that layer, and all the conductors of each layer being at the same radius from the axis of the rotor substantially throughout the lengths of the conductors, and end connections between the ends of the conductors of the first and second layers of the pair, the said end connections completing turns of the winding each of which turns comprises at least one conductor of the first layer connected in series with at least one conductor of the second layer, and each of the said end connections extending substantially radially between a conductor end of the first layer and an adjacent conductor end of the second layer.

In a machine having a winding of this configuration the arrangement of the conductors in cylindrical layers at a constant radius facilitates the provision of a strong mechanical support throughout the length of the winding. The displacement of the ends of the conductors allows the end connections to be made directly and reduces the requirement for end windings to connect conductors lying at spaced positions around the winding.

In a preferred construction the conductors each comprise a single helical section extending between the ends of the winding and extending through a helical passage in the support structure. The support structure is composed of a plurality of rings each of which

has for each layer of conductors a circle of inclined holes, the rings being assembled so that these holes are aligned to form the helical passages. All the rings are of the same form and they provide a uniform support for the conductors over substantially the whole length of the winding.

In alternative embodiments the path of each conductor from end to end of the winding may comprise two helically disposed sections of opposite hand, there being an abrupt change of direction of the conductor intermediate the ends of the winding. The lengths of the two sections of each helical conductor are preferably equal, but need not necessarily be so.

Where the winding forms the stator winding of a machine having a superconducting rotor field winding it preferably extends beyond the ends of the rotor winding so that the end connections lie in a region of lower field strength than the central parts of the conductors to reduce eddy current losses. Such a distribution may also be adopted with an air-gap armature winding for an iron-cored machine.

As in conventional windings, several turns can be connected in series to form a coil in windings of a machine according to the invention, successive turns being made of conductors lying adjacent to one another in the winding. A second coil whose conductors are displaced from those of the first coil around the axis of the cylindrical layers may be electrically connected in series or in parallel with the first coil. In a preferred construction the first and second coils are connected in series and in such a way that the current flows through the conductors of the two layers in opposite orders in the two coils.

In one embodiment the displacement between the ends of each conductor in each layer is approximately 180°, and each turn consists of a single conductor of each layer, and the first and second coils are displaced 180° from each other. In this embodiment the first and second coils form a coil set for one phase and similar coil sets are provided for two other phases each coil set being displaced 120° around the rotor. The conductors of each layer are spaced uniformly around the winding.

To enable the nature of the invention to be more readily understood various embodiments thereof will now be described by way of example with reference to the accompanying drawings, in which:—

Figure 1 is a developed diagram of a 3-phase stator winding of an a.c. generator in accordance with the present invention,

Figure 2 is a vertical section of an alternator of a type in which the stator winding may be constructed in accordance with the present invention,

Figure 3 shows an elemental ring of a stator winding support structure of a machine in accordance with the present invention,

Figure 4 is a cross-section through the ring shown in Figure 3, taken on the line x—x,

Figure 5 is a diagrammatic, partially cut-away, perspective view of a portion of a stator winding support structure formed of rings shown in Figure 3,

Figure 6 is a similar view to Figure 5 of an alternative stator winding support structure in which the elemental rings are composed of a plurality of segments,

Figure 7 is a diagrammatic exploded view of a stator winding support structure of a machine in accordance with the invention comprising three concentric hollow cylinders,

Figure 8 is a diagrammatic perspective view of one of the cylinders forming the support structure shown in Figure 7,

Figure 9 is an end elevation of the cylinder shown in Figure 8,

Figure 10 is a side elevation of the cylinder shown in Figures 8 and 9, and

Referring first to Figure 1, the winding diagram shown includes the complete coil set for one phase extending between the terminals A and A', but for the sake of clarity shows only the terminals B, B' and C, C' and the ends of the conductors of the other two phases.

The coil set between the terminals A and A' is made up of coils a_1—a_1' and a_2—a_2. The coil a_1—a_1' is composed of 10 turns each of which consists of a conductor X_1 of one layer and a conductor Y_1 of the other layer. The coil a_2'—a_2 is composed of 10 turns each of which consists of a conductor Y_2 of the second layer and a conductor X_2 of the first layer. The two coils are connected in series by an end connection between a_1' and a_2' such that whereas the current in coil a_1—a_1' flows first through a conductor X_1 and then through a conductor Y_1, that in the coil a_2'—a_2 flows first through a conductor Y_2 and then through a conductor X_2. The directions of current flow shown on the conductors are of course those for a particular instant of time since they will change as the rotor rotates and the rotor field cuts the conductors of the winding.

It will be noted that all the conductors X_1 and X_2 of the first layer, together with the coresponding conductors for the other two phases, have their ends displaced from one another around the stator in one sense, while all the conductors Y_1 and Y_2 of the second layer, with the conductors of the other phases, have their ends displaced in the opposite sense. Each of the conductors of the first layer follows a helical path comprising a single helical section of the same positive helix angle as the other conductors of the layer and each of the conductors of the second layer follows a helical path of the same negative helix angle as the other conductors of the

second layer. In this particular embodiment the helix angle is the same for both layers and the conductors in each layer are uniformly spaced around the stator.

It will also be noted that the ends of each conductor are circumferentially displaced relative to one another by 180° and thus the centre of each conductor is circumferentially displaced from the ends of the conductor by 90° or $\pi/2$ electrical radians relative to the rotor field. The coils a_1—a_1', and a_2'—a_2 are displaced relative to each other by 180° or π electrical radians relative to the rotor field.

It will further be noted that the interconnection of the coils a_1—a_1' and a_2'—a_2 is such that the armature reaction fluxes which they generate assist one another. This can conveniently be seen by considering the two diamond shapes which the conductors form at diametrically opposite points on the stator. Whereas the currents circulate clockwise about one diamond, they circulate anticlockwise around the opposite diamond and hence the flux entering at one side of the stator leaves at the opposite side.

The individual conductors are each finely subdivided and twisted to minimise eddy current losses. The end connections, which may be solid, but might also be subdivided, are located in a region of lower field strength. For this purpose the length:diameter ratio of the winding is preferably greater than 1.5.

Referring to Figure 2, the superconducting alternator shown comprises a superconducting rotor field winding 10 and a non-superconducting stator winding comprising stator conductors 11, and illustrates the preferred type of machine in which the present invention is employed. Whilst the stator conductors 11 are shown for convenience as straight conductor bars in Figure 2, they would follow helical paths in a machine according to the invention.

The field winding 10 is carried by a rotor consisting of an inner part 12 and an outer part 13 and is cooled by means of liquid helium circulating through a refrigerator 14 by way of supply and return connections 15. The space within the rotor is evacuated by way of a vacuum connection 16 to provide thermal isolation of the winding 10. The rotor outer part 13 serves as a vacuum casing and also forms an eddy current screen between the rotor and stator windings. The alternator stator consists of a stator outer casing 17 and a stator inner structure 18, the latter supporting the stator conductors 11. A copper screen 19 is supported by the outer casing 17 and surrounds the rotor and stator windings. The stator conductors 11 are directly fluid cooled by means of a water manifold 20. Figure 2 also makes clear the substantial amount by which the stator winding overlaps the rotor winding at both ends of the alternator.

Figures 3 and 4 illustrate an elemental ring from a number of which a winding support structure is produced to form the stator inner structure 18 of Figure 2. The ring includes two circles of inclined holes, holes 21 in the outer circle and holes 22 in the inner circle, only four holes in each circle being shown for clarity. Rings 25 shown in Figures 3 and 4 are assembled as shown in Figure 5 to provide helical passages through the structure. For clarity, only one such passage 23 is shown in Figure 5, passing centrally through the wall of the resultant hollow cylinder 24 produced by the assembly of rings 25, but in an asembly of rings as shown in Figures 3 and 4, the radially outer holes 21 would form helices winding in one sense around the stator bore, whilst the radially inner holes 22 would form helices of opposite hand. Holes 21 are thus arranged to receive conductors of the outer layer of the helical winding shown in Figure 1, whilst holes 22 receive conductors of the radially inner layer. Conductors which have been performed to a helical shape can be threaded through the helical passages, and short radial end connections are made at the ends of the passages to complete the turns.

The material of which the support structure is composed non-magnetic and preferably non-conducting, a suitable example being densified hardwood.

In the construction shown in Figure 6, each elemental ring is composed of segments, such as segments 31*a*—38*a* of the end ring *a* shown. With this arrangement, the segments are threaded over conductors one at a time (the conductors passing through holes, not shown, in the segments), which may in some cases facilitate assembly.

An alternative winding support structure is shown in Figures 7 to 10, in which the hollow cylindrical structure is composed of three cylinders 43, 44 and 45 juxtaposed about each other, but shown exploded in Figure 7. This form of construction permits the conductors to be disposed in grooves on the outer surface of either or both inner cylinders. The path 46 of a helical groove for an inner layer conductor is indicated on cylinder 43, whilst the path 47 of a helical groove of opposite hand is shown on cylinder 44. One of the grooves 48 in the cylinder 44 shown in more detail in Figures 8 to 10, by way of example.

In an alternative form of winding in a machine according to the invention, each conductor in a layer follows a path from end to end of a support cylinder in two sections, of which one section follows a helical path of one hand whilst the other section follows a helical path of opposite hand. Over each axial half of the winding, however, the conductor sections in the upper layer follow helices of opposite hand to the conductor sections of the lower layer.

In windings of the form shown in Figure

1 and in the alternative form just described, it should be noted that each conductor or conductor section of a layer bears the same spatial relationship to the remaining conductors of the winding as every other conductor of that layer. The self-inductance of the coils formed, and the mutual inductances between coils, is thus made equal, thus enabling symmetrically balanced windings to be produced. All the conductors of each layer are at the same radius from the axis of the rotor substantially throughout the lengths of the conductors.

The embodiment described with respect to Figure 1 is a simple two-pole, three-phase winding, but it will be apparent that windings having any combination of the number of pole pairs, the number of phases and the supply frequency, fall within the scope of the invention. In all such possible arrangements, it is simply required that the pitch of the conductors in the various layers be arranged so that the ends of the conductors to be joined come to lie as far as possible adjacent one another.

WHAT WE CLAIM IS:—

1. An alternating-current dynamo-electric machine having a rotor, and a stationary alternating current winding carried by a non-magnetic hollow cylindrical support structure coaxial with the rotor, the winding including a pair of coaxial cylindrical layers of conductors of which each conductor is composed of one or more sections of helical formation, each conductor of a layer having the same spatial relationship to the other conductors of the winding as every other conductor of that layer, and all the conductors of each layer being at the same radius from the axis of the rotor substantially throughout the lengths of the conductors, and end connections between the ends of the conductors of the first and second layers of the pair, the said end connections completing turns of the winding each of which turns comprises at least one conductor of the first layer connected in series with at least one conductor of the second layer, and each of the said end connections extending substantially radially between a conductor end of the first layer and an adjacent conductor end of the second layer.

2. A machine as claimed in claim 1 in which each conductor comprises a single helical section extending from end to end of the winding, the helical sections of the first layer being of opposite sense to those of the second layer.

3. A machine as claimed in claim 1 or 2, in the stationary winding is a multi-phase winding having a set of two series-connected coils for each phase.

4. A machine as claimed in claim 3 in which each turn of each coil of a set comprises a conductor of the first layer in series with a conductor of the second layer, the conductors of the two layers having equal helix angles, and the centre of each conductor being circumferentially displaced from the end of the said conductor by $\pi/2$ electrical radians with respect to the rotor field.

5. A machine as claimed in claim 3 or 4 in which the two coils of each phase are displaced relative to each other around the circumference of the winding by π electrical radians relative to the rotor field.

6. A machine as claimed in claim 1 in which several turns are connected in series to form a coil, successive turns being made up conductors lying adjacent to one another in the winding.

7. A machine as claimed in claim 6 in which a second coil whose conductors are displaced from those of the first coil around the axis of the cylindrical layers is electrically connected to the first coil.

8. A machine as claimed in claim 7 in which the first and second coils are connected in series but the current flows through the conductors of the two layers in the opposite order in the two coils.

9. A machine as claimed in claim 8 in which the displacement between the ends of each conductor in each layer is approximately 180°, each turn includes a single conductor of each layer, and the first and second coils are displaced 180° from each other.

10. A machine as claimed in claim 1 in which each conductor of each layer comprises a first and a second helical section of equal length and opposite sense, the first and second sections of the conductors of the second layer overlying and being of opposite sense to the first and second sections, respectively, of the conductors of the first layer.

11. A machine as claimed in any of the preceding claims in which the hollow cylindrical support structure has a wall provided with helical passages in which the conductors are retained.

12. A machine as claimed in claim 11 which the wall of the support structure is composed of a plurality of elemental rings each of which has, for each layer of conductors, a circle of inclined holes, the holes in successsive rings being aligned to form the said helical passages.

13. A machine as claimed in claim 12 in which each of the elemental rings is composed of a plurality of segments.

14. A machine as claimed in claim 11 in which the wall of the support structure is composed of at least two coaxial hollow cylinders juxtaposed one about the other.

15. A machine as claimed in claim 11 in which the wall of the support structure is composed of at least two coaxial hollow cylinders juxtaposed one about the other, the curved surface of at least one cylinder having helically-disposd grooves which in

conjunction with the adjacent curved surface of an adjoining cylinder form the said helical passages.

16. A machine as claimed in any of the preceding claims in which the rotor carries a superconducting field winding.

17. A machine as claimed in claim 16 in which the axial length of the stationary winding is substantially greater than that of the rotor winding and the stationary winding extends beyond both ends of the rotor winding.

18. A machine as claimed in any of the preceding claims in which a stator of magnetic material surrounds the rotor with a cylindrical air gap between the rotor and the stator, and the stationary winding is disposed in the air gap.

19. An alternating-current dynamo-electric machine substantially as described with reference to Figure 1 or Figures 1 and 2, or Figures 1 to 5 of the accompanying drawings.

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